

Does the Mass Accretion Rate Depend On the Radius of the Accreting Star?

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ABSTRACT

In some circumstances, the mass accretion rate \dot{M}_\star onto a compact star may depend not only on external boundary conditions, but also on the radius R_\star of the star. Writing the dependence as $\dot{M}_\star \propto R_\star^p$, we estimate p for transient binary systems in a quiescent state. We use the observed luminosities L of accreting neutron stars ($R_\star \sim 10^6$ cm) in soft X-ray transients and white dwarfs ($R_\star \sim 10^9$ cm) in similar cataclysmic variables, and estimate \dot{M}_\star in each system through the relation $L \approx GM_\star \dot{M}_\star / R_\star$, where M_\star is the mass of the star. From the available data we infer that $p \sim 0.9 \pm 0.5$. This radial dependence is consistent with radiatively inefficient accretion flows that either are convective or lose mass via a wind.

1. Introduction

For steady accretion onto a compact object, it is often assumed that the mass accretion rate onto the central star \dot{M}_\star is determined only by boundary conditions at some large radius where the gas is initially introduced into the accretion flow. This assumption is valid for a number of idealized accretion solutions: (i) spherical accretion (Bondi 1952), (ii) steady accretion via a thin disk (Shakura & Sunyaev 1973; Novikov & Thorne 1973), and (iii) steady accretion via an advection-dominated accretion flow (ADAF; Ichimaru 1977; Narayan & Yi 1994; 1995a,b; Abramowicz et al. 1995; Chen et al. 1995).

Recently, it has become clear that under some circumstances \dot{M}_\star may depend not only on outer boundary conditions but also on the radius of the central star R_\star . A power-law dependence has been proposed:

$$\dot{M}_\star \propto R_\star^p. \quad (1)$$

Gruzinov (1998), for instance, argued that spherical accretion in the presence of strong conduction behaves according to equation (1), with p of order unity.

In the case of a thin accretion disk, it has been known for a number of years that large changes in the opacity of the accreting gas as a result of hydrogen ionization lead to a thermal instability (see Cannizzo 1993 for a review). This instability causes the well-known transient behavior of accreting white dwarfs (WDs) in cataclysmic variables (CVs), and accreting neutron stars (NSs)

and black holes in soft X-ray transients (SXTs). If accretion in the quiescent state of transient binaries occurs via a pure thin disk (which is in some doubt, see below), then \dot{M}_* is expected to scale according to equation (1) with a large value of $p \sim 2.7$ (Ludwig, Meyer-Hofmeister & Ritter 1994; Hameury et al. 1998; Menou et al. 1999a).

In the case of advection-dominated accretion, the radius of the star can again be important in some circumstances. For instance, if there are strong outflows, as seems likely (Narayan & Yi 1994, 1995a), the mass accretion rate is expected to behave as in equation (1). Blandford & Begelman (1999) suggested that ADAFs with outflows, which they named ADIOS, may have values of p in the range $0 - 1$. Igumenshchev & Abramowicz (1999, 2000) found ADIOS-like flows in numerical simulations when they used large values of the viscosity parameter $\alpha > 0.3$. Their simulations suggest that $p \sim 0.3 - 0.5$; this estimate is, however, very approximate since the results from the simulations are not consistent with a power-law behavior.

Narayan & Yi (1994, 1995a) argued that advective flows should, in addition to having outflows, also be convectively unstable. Igumenshchev & Abramowicz (1999, 2000) found well-developed convection in numerical simulations when they used small values of $\alpha < 0.1$. These convective flows correspond to a new form of quasi-spherical accretion (Stone, Pringle & Begelman 1999), which is called a convection-dominated accretion flow or CDAF. Both the numerical simulations and analytical work (Narayan, Igumenshchev & Abramowicz 2000; Quataert & Gruzinov 2000; Igumenshchev, Abramowicz & Narayan 2000) show that CDAFs follow equation (1) with $p \sim 1$.

In this *Letter* we are concerned with transient binaries such as CVs and SXTs. Narayan, McClintock & Yi (1996) and Lasota, Narayan & Yi (1996) argued that quiescent SXTs cannot have pure thin disks; a similar argument had been made earlier by Meyer & Meyer-Hofmeister (1994) for CVs. Narayan et al. (1996) suggested that SXTs, and by extension CVs, have composite accretion flows in which a thin disk is present at large radii, beyond $\sim 10^9 - 10^{10}$ cm, and an ADAF is present at smaller radii. In view of the recent work described above, it is possible that, rather than an ADAF, the inner flow might consist of an ADIOS or a CDAF. We thus have four different possibilities for the accretion flow in quiescent CVs and SXTs, each with a different prediction for p ; (i) pure thin disk ($p = 2.7$), (ii) ADAF ($p = 0$), (iii) ADIOS ($p \sim 0.3 - 0.5$), and (iv) CDAF ($p \sim 1$).

Theoretical analysis is presently incapable of discriminating among these four possibilities. Here we use a novel empirical method to infer the value of p .

We consider CVs and SXTs with similar orbital periods (in the range $\sim 2 - 20$ hours), which ensures that the outer boundary conditions of their accretion flows are similar. The mass transfer rate from the companion star in a semi-detached binary system depends primarily on the binary period, and is fairly insensitive to the mass of the compact star (Menou et al. 1999a). This is especially true for systems with orbital periods of a fraction of a day or shorter, in which mass transfer is driven primarily by gravitational radiation losses. Thus, for the CVs and SXTs considered here, the mass supply rate is likely to be similar.

On the other hand, the radius of the accreting star in the systems we consider spans a wide range, from $\sim 10^9$ cm for WDs in CVs to $\sim 10^6$ cm for NSs in SXTs. For accretion onto a star with a hard surface (as distinct from a black hole, see Narayan, Garcia & McClintock 1997), the accretion luminosity L has a simple dependence on R_\star and \dot{M}_\star :

$$L \approx \frac{GM_\star \dot{M}_\star}{R_\star}, \quad (2)$$

where M_\star is the mass of the accreting star. Therefore, given the observed L , and estimates of M_\star and R_\star , we may infer the value of \dot{M}_\star . Since we select systems with similar outer boundary conditions, but with a wide range of R_\star , we should be able to estimate the dependence of \dot{M}_\star on R_\star , and thus the value of p . Note that correction factors of order unity are unimportant in this analysis, because the value of the gravitational potential $GM_\star/R_\star c^2$, or equivalently $L/\dot{M}_\star c^2$, differs by three orders of magnitude between NSs and WDs.

Before proceeding, we note that Medvedev & Narayan (2000) recently obtained a new hot quasi-spherical accretion solution which applies under some circumstances to a rotating star with a surface. The luminosity of this solution does not scale according to equation (1), but depends primarily on the radius and the spin of the star. The estimate of p derived in this *Letter* would not be valid if accretion in the CVs or NS SXTs we consider is described by this solution.

In §2 we present the available data on the luminosities of WDs (§2.1) and NSs (§2.2) with similar binary periods and companions. In §3, we use the data to infer the best-fit value of p . Finally, we summarize our conclusions and discuss their implications in §4.

2. Luminosity Data

2.1. White Dwarfs

CVs have been extensively studied at X-ray, UV and optical wavelengths. In recent years, UV spectroscopy has provided WD temperatures for a number of systems. The sample of NS SXTs discussed in §2.2 has orbital periods in the range 2 – 20 hours, with a geometric mean of about 6 hours. CVs typically have somewhat shorter orbital periods. In order to make a fair comparison, we focus our attention on non-magnetic CVs with periods greater than 3 hours. Most of the long period systems are high accretion rate Nova-like variables whose UV spectra are dominated by their accretion disks and whose WD temperatures are not known. There are six CVs with low \dot{M} which are suitable for the comparison (Table 1). For the basic parameters, we take periods (P), WD masses (M_{wd}), V-band luminosities (L_v) and distances (d) from Ritter & Kolb (1999), WD temperatures (T_{wd}) from Sion (1999) and X-ray luminosities (L_x) from the ROSAT All Sky Survey tabulation of Verbunt et al. (1997). WD radii (R_{wd}) are derived from the masses and the mass-radius relation (Hamada & Salpeter 1961). The six selected systems have orbital periods in the range 3.3 to 6.6 hours, with a geometric mean of about 5 hours, not very different from the mean period of the NS SXTs (6 hours).

We have substituted more recent parameter determinations in several cases. The distances for SS Cyg and U Gem are those based on HST FES parallaxes (Harrison et al 1999), which are more reliable than other distance estimates. The X-ray luminosities of SS Cyg and U Gem are derived by scaling the GINGA spectrum of Yoshida, Inoue & Osaki (1992) and the ASCA spectrum of Szkody et al. (1996) to the Harrison et al. (1999) distances, because luminosities based on ROSAT are less reliable for hard sources. The WD temperature, mass and radius for U Gem are taken from Long (2000), who finds that a combination of 85% of the surface of the star at 30,000 K and 15% at 50,000 K fits the UV spectrum. This results in the WD luminosity quoted in Table 1. The limit on the WD temperature for IP Peg is from Froning et al. (1999), but uncertainties in the luminosity are relatively high for this edge-on system. The distance limit for TZ Per is from Ringwald (1995).

DW UMa is a special case. Knigge et al. (2000) present a detailed analysis of HST spectra. By chance, the observations occurred during a remarkable low state for this SW Sex star, when it was 3 magnitudes fainter than its normal brightness. Knigge et al. (2000) were able to derive the temperature, mass and radius of the WD, but no X-ray observations in the low state are available. Moreover, WDs in CVs are heated during high \dot{M} states and cool gradually after \dot{M} drops, with characteristic times of months (see the review by Sion 1999). Therefore, it is probable that DW UMa was cooling from its high \dot{M} state during the HST observation, and we take the rather high WD luminosity as an upper limit to the accretion luminosity.

Note that we are making the unconventional assumption that the white dwarf luminosity is the accretion luminosity in the low state. The consequences of other assumptions are discussed in §4. ADAF models predict $L_{wd} = L_{acc}$. Conventional boundary layer models (Pringle & Savonije 1979; Tylenda 1981) predict only $L_{wd} \sim 0.5L_x$ from the heated surface of the white dwarf, although some models of optically thick boundary layers advect a significant fraction of the luminosity into the star (Regev 1983). The soft X-ray excess of some AM Her stars is a clear, if poorly understood, example of advection of accretion energy into the white dwarfs in magnetic CVs.

The WDs in dwarf novae are heated during outbursts, and cool during the quiescent phase. Cooling times are fairly short, with values of 30 days and 6 days estimated for U Gem and RX And, respectively (Long et al 1993; Sion 1999). Compressional heating throughout the WD (Sion 1995) reflects the long-term average accretion rate. We have no reliable way to remove the effects of heating during outburst or compressional heating, though we have tried to select WD temperatures far after outburst when possible. Therefore, it must be borne in mind that some fraction of L_{wd} may arise from causes other than accretion during the quiescent phase. However, as noted in §1, factors of ~ 2 – 3 have little effect on our quantitative conclusions.

2.2. Neutron Stars

Table 1 shows the 0.5–10 keV X-ray luminosities of all NS SXTs for which data are available. The luminosity of SAX J1808.4-3658 is from Stella et al. (2000), and those of the other four sources are from Narayan et al. (1997) and Menou et al. (1999b). The latter authors give the luminosity of one other NS SXT, H1608-52, which has $\log[(L_x/\text{erg s}^{-1})] = 33.3$. However, this source does not have a reliably measured orbital period; the period could be either 5 hours (Chen et al. 1998) or 98.4 hours (Ritter & Kolb 1998). Since it is important for our method to select systems with comparable orbital periods (so that the outer boundary conditions for the accretion flows are similar), we do not include this system.

The values tabulated in Table 1 may be regarded as estimates of the total (bolometric) luminosities of the systems since a substantial fraction of the emission is expected to come out in the 0.5–10 keV band. In the case of Cen X-4 in quiescence, McClintock & Remillard (2000) have measured the optical-UV spectrum and shown that the luminosity in these bands is comparable to the X-ray luminosity. Assuming that this source is typical, we expect the 0.5–10 keV luminosity to underestimate the bolometric luminosity by a factor of 2 or so.

A more difficult issue is deciding what fraction of the X-ray luminosity is derived from accretion. Recently, Brown, Bildsten & Rutledge (1998) showed that crustal heating of NSs in SXTs during outburst could lead to quiescent thermal emission from the cooling NSs at a level comparable to the observed luminosities of quiescent NS SXTs. Could the entire observed L_x be due to this cooling radiation?

At least two of the five NS SXTs listed here have shown substantial variability: Cen X-4 (Campana et al. 1997) and SAX J1808.4-3658 (Dotani, Asai & Wijnands 2000). Such variability is not expected for a cooling NS. Also, the X-ray spectra of two quiescent systems show significant power-law tails: Cen X-4 (Asai et al. 1996) and Aql X-1 (Campana et al. 1998). Again, it is unlikely that the power-law emission arises from thermal cooling. Barring the somewhat extreme possibility that quiescent NS SXTs behave similarly to radio pulsars and have significant magnetospheric activity (as proposed by Campana & Stella 2000), we feel that there is a strong case for assuming that at least the power-law emission (which has roughly half the power) is due to accretion. Thus, the accretion luminosities of the NS SXTs considered are probably between $\sim 50\%$ and 100% of the luminosities listed in Table 1 (50% if only the power-law spectral component is from accretion, and 100% if the thermal component is also from accretion). In Figure 1 and the analysis presented in §3, we assume 100% . (Equivalently, we assume 50% and apply a bolometric correction of a factor of 2.)

3. Inferred Mass Accretion Rates and Estimate of p

Using the accretion luminosities in Table 1, we may now estimate the mass accretion rates from equation (2). We assume that all NSs have the same mass, $M_\star \approx 1.4M_\odot$ (Thorsett & Chakrabarti 1999), and radius, $R_\star \approx 10^6$ cm (Shapiro & Teukolsky 1983). For the WDs, we use the masses and radii given in Table 1.

Figure 1 shows two clusters of points corresponding to WD and NS systems in quiescence. The three lines show power-law scalings with different slopes, $p = 0.4, 0.9$ and 1.4 , all originating from the logarithmic average of \dot{M}_\star for NS systems. Since the WD points are roughly bounded by these lines we infer that $\dot{M}_\star \propto R_\star^{0.9 \pm 0.5}$ for accretion flows in quiescence around compact stars. The central value of p is close to unity, in agreement with the expected behaviour of convection-dominated accretion flows (CDAF).

4. Conclusions

The accretion luminosities of NSs and WDs in quiescence with similar binary companions are comparable (see Table 1). This surprising result implies that the accretion rate at the surface of a WD, namely $\dot{M}_\star(10^9$ cm), is larger by three orders of magnitude than that on the surface of a NS, $\dot{M}_\star(10^6$ cm). In both cases the radius of the hard surface where the accretion flow terminates is much smaller than the outer boundary of the accretion flow, and hence the flow should exhibit a similar behaviour on scales larger than its inner edge. Figure 1 implies that the mass accretion rate varies with radius roughly as $\dot{M}_\star \propto R_\star^{0.9 \pm 0.5}$. This behaviour is remarkably similar to that predicted for CDAFs (Narayan et al. 2000; Quataert & Gruzinov 2000; Igumenshchev et al. 2000). The data are marginally consistent with an ADIOS model (Blandford & Begelman 1999), for which Igumenshchev & Abramowicz (1999, 2000) found $p \sim 0.3 - 0.5$. The data do not support the assumption of a constant \dot{M}_\star , as in a pure ADAF model (e.g. Narayan et al. 1996), or a very steep scaling ($p \sim 2.7$) as in a pure quiescent thin disk (e.g. Menou et al. 1999a).

Unfortunately, the quantitative results are subject to large uncertainties due to the small number statistics of the relevant systems. They could also be affected by a number of systematic effects. One potential systematic effect is probably not important, namely we do not believe that there is a serious bias in the sample of systems we have used. Our sample of CVs is an unbiased sample of binaries with orbital periods in the range of interest. Also, virtually all known NS SXTs have been detected in X-rays in quiescence; therefore, the sample of NS SXTs in Table 1 is likely to be complete and unbiased (except for the one system we did not include because its period is not known, see §2.2).

One potentially important systematic effect is related to the fact that the luminosities in Table 1 may not represent just the accretion luminosities in quiescence, but may also include a cooling component which originates from the heat deposited in the accretor during an earlier high

\dot{M} (outburst) state. If some of the quiescent emission in CVs is due to the cooling of the WD (Sion 1999), then p would be smaller than the value we obtained; in principle, if the accretion luminosity in quiescent CVs is very much smaller than the observed luminosity, p could be as small as zero, as required for a pure ADAF model. The luminosity of a cooling WD should decay with time in a predictable fashion, so this scenario could be tested with careful observations of the CVs listed in Table 1. On the other hand, if the quiescent luminosities of NS SXTs are primarily due to NS cooling (as proposed by Brown et al. 1998), then p would be larger than our estimated value, perhaps as large as the 2.7 predicted for a pure thin disk. For the reasons given in §2.2, we consider this unlikely.

A systematic effect with an opposite sign involves the possibility that we have underestimated the bolometric luminosities of the systems under consideration by ignoring the emission at unobserved photon frequencies. This is probably not a serious problem, as CVs appear to radiate primarily in optical, UV and EUV, where there are adequate observations, and NS SXTs emit primarily in the X-ray band (see §2.1 and §2.2).

Finally, it is possible that magnetic fields of NSs or WDs reduce the mass accretion rate onto the star, thereby giving an artificially low estimate of \dot{M}_* . This is more likely in NS SXTs than in CVs (Menou et al. 1999b). If the effect is important, then p would be smaller than our estimate.

A key aspect of our analysis is the relation between the mass accretion rate and the luminosity given in equation (2). This formula is valid so long as the accreting star has a hard surface. If the accretor is a black hole, and if accretion occurs via a radiatively inefficient flow, such as an ADAF or an ADIOS or a CDAF (but not a thin disk), then the accretion luminosity is expected to be significantly less than that given in equation (2). This is because the energy advected with the accretion flow can disappear through the event horizon (Narayan & Yi 1995b; Narayan et al. 1997). The quiescent luminosities of BH SXTs do appear to be significantly lower than the luminosities of NS SXTs. This is consistent with the presence of an event horizon in black hole SXTs (Narayan et al. 1997; Menou et al. 1999b).

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Table 1: Accretion Luminosities in Quiescence (in erg s^{-1})

White Dwarf (CVs)									
Object	$P(\text{hr})$	$M_{wd}(M_{\odot})$	$\log(T_{wd}/\text{K})$	V	d(pc)	$\log(R_{wd}/\text{cm})$	$\log L_x$	$\log L_v$	$\log(L_{wd})$
RX And	5.02	1.14 ± 0.33	35,000	12.6	135	8.63	30.0	31.9	32.3
SS Cyg	6.60	1.19 ± 0.02	37,000	11.4	166	8.62	32.6	32.6	33.0
U Gem	4.25	1.02 ± 0.04	30,000*	14.0	96	8.75	31.2	31.5	32.6
IP Peg	3.80	1.15 ± 0.10	< 15,000	17.8	124	8.63	< 29.5	30.4	30.8
TZ Per	6.31	(1.0)	18,000	15.6	(> 380)	(8.76)	(> 30.4)	31.6	31.4
DW UMa	3.28	0.48 ± 0.06	46,000	17.6	830	9.11		31.4	33.7

Neutron Star (SXTs)		
Object	P (hr)	Log (L_x [0.5-10 keV])
SAX J1808.4-3658	2	32.4
EXO 0748-676	3.8	34.1
4U2129+47	5.2	32.8
1456-32 (Cen X-4)	15.1	32.4
1908+005 (Aql X-1)	19	32.6

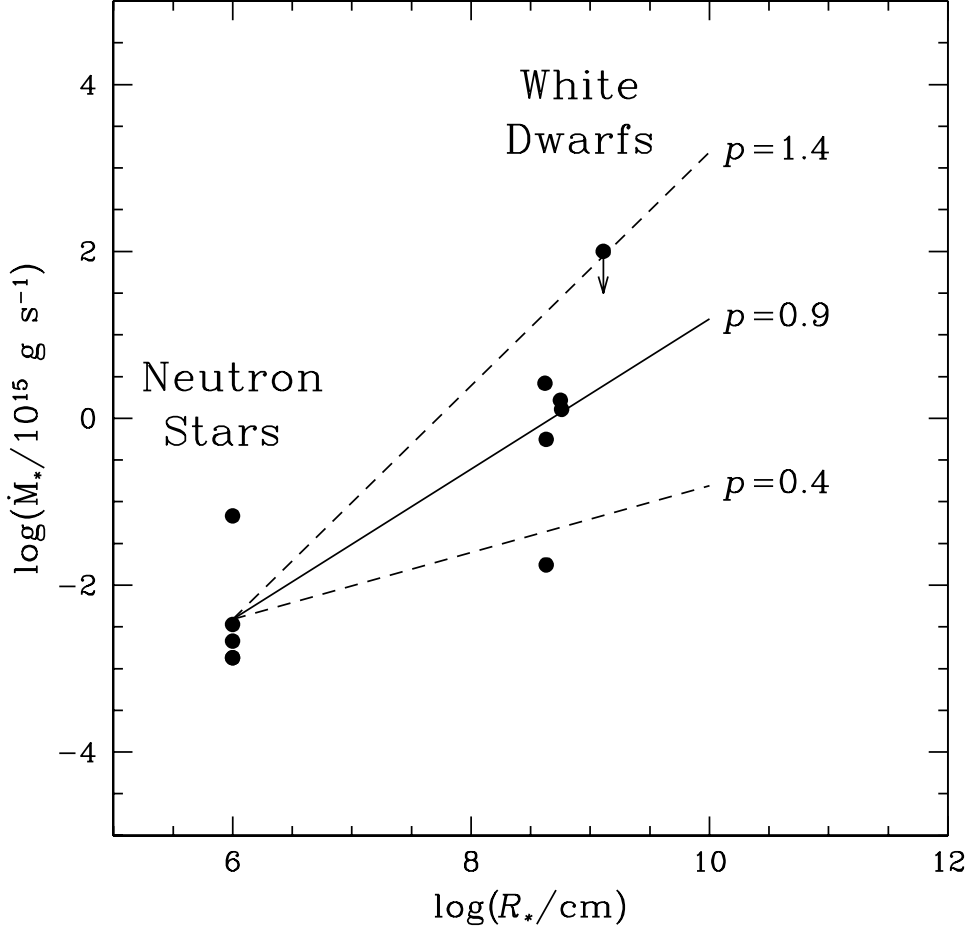


Fig. 1.— Mass accretion rate vs radius, $\dot{M}_*(R_*)$, for white dwarfs (WD) and neutron stars (NS) which accrete mass from binary companions with similar orbital periods. The points were inferred from the data in Table 1 using Eq. (2). The solid line originates at the (logarithmic) average of \dot{M}_* for the NS points and goes through the average \dot{M}_* for the WD points. It corresponds to a power-law scaling with an index $p = 0.9$ [Eq. (1)], while the dashed lines correspond to $p = 1.4$ (upper line) and $p = 0.4$ (lower line).